

4th IAA Planetary Defense Conference – PDC 2015
13-17 April 2015, Frascati, Roma, Italy

IAA-PDC-15-0X-XX

PHYSICS-BASED MODELING OF METEOR ENTRY AND BREAKUP

**Dinesh K. Prabhu⁽¹⁾⁽¹³⁾, Parul Agrawal⁽²⁾⁽¹³⁾, Gary A. Allen, Jr.⁽³⁾⁽¹³⁾,
Charles W. Bauschlicher, Jr.⁽⁴⁾, Aaron M. Brandis⁽⁵⁾⁽¹³⁾, Yih-Kang Chen⁽⁶⁾,
Richard L. Jaffe⁽⁷⁾, Grant E. Palmer⁽⁸⁾⁽¹³⁾, David A. Saunders⁽⁹⁾⁽¹³⁾,
Eric C. Stern⁽¹⁰⁾⁽¹³⁾, Michael E. Tauber⁽¹¹⁾⁽¹³⁾, and Ethiraj Venkatapathy⁽¹²⁾**

⁽¹⁾ Mail Stop 229-1, NASA Ames Research Center, Moffett Field, CA 94035, USA.

ARC, 650 604 1145, dinesh.k.prabhu@nasa.gov

⁽²⁾ ARC, 650 604 3764, parul.agrawal-1@nasa.gov

⁽³⁾ ARC, 650 604 4228, gary.a.allen@nasa.gov

⁽⁴⁾ ARC, 650 604 6231, charles.w.bauschlicher@nasa.gov

⁽⁵⁾ ARC, 650 604 0888, aaron.m.brandis@nasa.gov

⁽⁶⁾ ARC, 650 604 3742, yih-kanq.chen-1@nasa.gov

⁽⁷⁾ ARC, 650 604 6458, richard.l.jaffe@nasa.gov

⁽⁸⁾ ARC, 425 482 4366, grant.e.palmer@nasa.gov

⁽⁹⁾ ARC, 650 604 1480, david.a.saunders@nasa.gov

⁽¹⁰⁾ ARC, 650 604 5690, eric.c.stern@nasa.gov

⁽¹¹⁾ mtauber@earthlink.net

⁽¹²⁾ ARC, 650 604 4282, ethiraj.venkatapathy-1@nasa.gov

⁽¹³⁾ ERC, Inc. at NASA Ames Research Center, Moffett Field, CA 94035, USA

Keywords: *Planetary Defense, Potentially Hazardous Asteroids, Meteor Entry and Breakup*

1. Introduction

The airburst on February 15, 2013 of a superbolide (approximately 20 m in size) over the Russian city of Chelyabinsk has given a new impetus, and a renewed sense of urgency, to planetary defense programs across the globe. In addition to the ongoing efforts in the detection and characterization of Potentially Hazardous Asteroids (PHAs), and developing strategies to mitigate the risk of potentially devastating impacts of large size (0.5 km or larger) PHAs, there is new interest in understanding and quantifying the risk of airburst/impact of PHAs that are much smaller than 0.5 km.

In October 2014 NASA's Near Earth Object (NEO) Program Office initiated a new effort in Planetary Defense (PD) at Ames Research Center (ARC). A companion to the present paper, by Arnold and Burkhard [1], provides the objectives and details of this new program, which integrates experiment and analysis in the areas of planetary science [2], entry physics (present work), and blast wave physics into a physics-based risk assessment framework [3]. Briefly, the research endeavor aims to determine scenario-based probabilities of the outcomes of impacts of PHAs of various sizes and various spectral classes (stony, stony-iron, iron, etc.), thus helping decision makers develop mitigation strategies. The present paper provides an overview of the work conducted for the entry physics task of the ARC PD program.

2. Objectives

We have undertaken the effort to extend and apply tools used for design and analysis of atmospheric entry capsules to the problem of entry of meteoroids, with the overarching objectives of understanding energy deposition into the atmosphere and fragmentation. Since the effort is still in its early stage, the near term objectives (for the purposes of the present paper) are: (i) to explore the physics of atmospheric entries of meteoroids using our current state-of-the-art tools and processes, (ii) to verify results of computations against results from models widely accepted by the meteor physics community, (iii) to explore the influence of shape (and shape change) on flow characteristics, and (iv) to explore how multiple bodies interact. In time we hope to improve both the tools and our understanding of the physics of energy deposition and break up, thereby adding more fidelity into the risk assessment tools.

3. Methodology and Assumptions

The methodology we have chosen to adopt in the initial phase of our effort is briefly described below.

1. We parameterize the flight space (the concept is described in more detail in the work of Prabhu et al. [4]) by the flight velocity, freestream density (altitude), and object size in an attempt to determine scaling laws for use in trajectory computations. This parameterization delinks flight trajectories from computations of the aerothermal environments around the meteoroid.
2. We consider only regular (and smooth) geometries, such as spheres and prolate spheroids. Having one axis (or axes) of symmetry considerably simplifies the effort in generating volume meshes. Furthermore, the use of simple geometries helps us tie into the work done in the meteor physics community. We note that the flow computations are not necessarily restricted to single objects. We also perform 3D computations for a finite collection of objects (still regular smooth geometries) to understand the interactions of the objects.
3. Flow computations are performed in the parameterized flight space without making assumptions about the meteoroid material and/or internal structure. Computations include estimation of high-temperature shock layer radiation. The results of computations at the end of this step are to be considered bounding because they do not include the thermal response of the material being heated by convection and radiation.
4. The computed environments are then used in: (1) trajectory software development, (2) material structural and thermal-structural response, and (3) material thermal response. The expectation is that the responses will be fed back into flow simulations, i.e., the thermal and structural response models are loosely coupled to the flow model. The feedback (chemical species and shape change) from the response models helps quantify the amount of energy attenuation due to ablation.

The altitude-velocity plot shown in Fig. 1 contains the flight space (quadrilateral) used in the present work. Also shown in the figure are the best-estimated trajectory (BET) for Stardust [5], and data for the Chelyabinsk bolide [6]. At each point shown in the flight space (filled diamonds in Fig. 1), flow computations are performed for regular geometries (hemispheres for now) of sizes ranging from 1 m to 100 m.

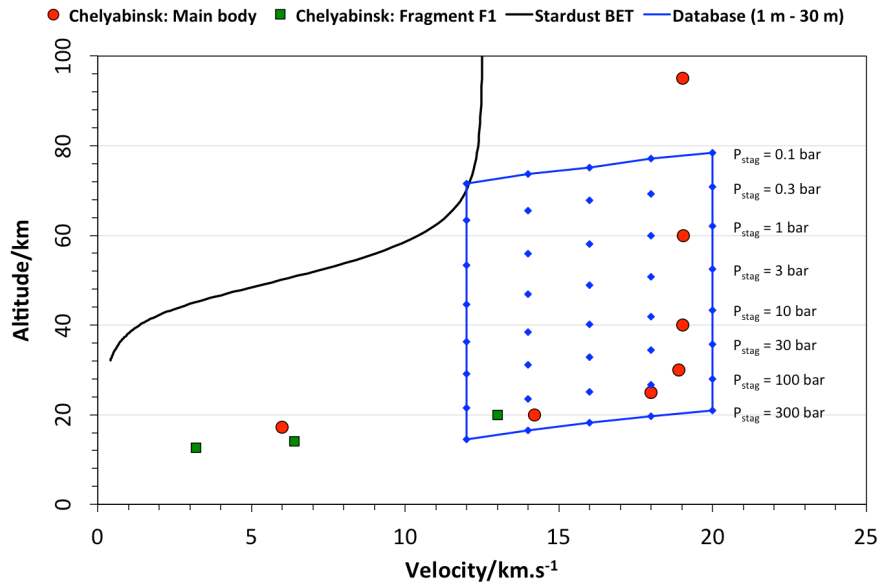


Figure 1. Flight space parameterization for flow computations. A velocity range of 12 to 20 km/s is covered for stagnation pressures ranging from 0.1 to 300 bar (0.01–30 MPa).

As is seen from Fig. 1, we have considered velocities from 12 to 20 km/s (equivalently 72 MJ/kg to 200 MJ/kg of kinetic energy). The state-of-the-art analysis tools and processes are calibrated to the Stardust mission (see the special issue of *Journal of Spacecraft and Rockets*, **47**(6), 2010), which is at lowest end of the velocity space that we have to explore for meteor entries. Therefore, application of these tools to Chelyabinsk-like meteor entries is a significant challenge.

From the computed flowfields, the surface pressure, shear stress (magnitude), and heat flux are extracted. The drag coefficient, C_D , is determined by integrating the pressure and shear stress distributions, and the heat transfer coefficient, C_H , is determined by integration of the total heat flux (convective and radiative) distributions. Finally, with a view towards developing a synthetic light curve, the energy radiated outward (*i.e.*, luminosity) from the shock layer into a hemisphere enclosing the bow shock is calculated. Although radiation energy flux computations are performed over the wavelength range of 85–39600 nm (VUV to IR), the wavelength range is restricted to 200–800 nm (middle UV to visible) in the computation of luminosity.

4. Analysis Tools

The primary modeling and simulation tools are:

1. *TRAJ* [7]: A 3DoF trajectory simulation code. The code has a variety of atmospheric models (for all relevant planets and moons in the Solar System), and gravitational and rotating planet models. For the present work, it has been updated to include a simple differential equation for mass loss, with heat transfer coefficients obtained from detailed flowfield computations via correlations.
2. *DPLR* [8]: A 3D Navier-Stokes flow solver for hypersonic flows. The code includes models for shock-layer thermochemical nonequilibrium, and a variety of surface boundary conditions. In the present work we have an 11-species air model (N_2 ,

O_2 , NO , N_2^+ , O_2^+ , NO^+ , N , O , N^+ , O^+ , and e^-) in thermal equilibrium (i.e., a single temperature is used for the flowfield). This choice of model limits us to velocities not exceeding 20 km/s, since thermodynamic, transport, and rate data for higher stages of ionization of N and O are still being developed. In all computations the wall (surface of the meteoroid) is assumed to be at 300 K and fully catalytic to atom recombination. Radiative equilibrium (hot wall) computations have been deferred until the material thermal response code is fully operational for meteoritic materials.

3. *NEQAIR* [9]: A line-by-line spectral code with the tangent-slab approximation for transport of radiation energy. The code is applied to lines of sight distributed over the surface. The data along a line of sight, T and n_s (temperature and number densities of species) are extracted from the flow field solution. The methodology developed by Palmer et al. [10] for loosely coupling the radiation code, *NEQAIR*, to the flow solver, *DPLR*, has been applied to a small number of cases in the flight space. Since such a coupled computation is not only expensive but also somewhat sensitive to the frequency of updates/interchanges between the flow and radiation fields, an empirical relation [11] is used to correct the adiabatic value obtained by *a posteriori* computations of radiation from the other converged flow field solutions.
4. *FIAT* [12] and *TITAN* [13]: One- and two-dimensional material thermal response codes. These codes rely on the idea of vapor blowing from the heated surface. The non-dimensional blowing rates, referred to as B-prime tables, are constructed separately for the desired range of surface temperatures and pressures. B-prime tables are readily available for materials typically used in the thermal protection system of entry capsules. However, construction of such tables for each meteor type (spectral class) is ongoing work. These codes too can be loosely coupled to the flow solver, *DPLR*.
5. *MARC* [14]: Commercial finite-element analysis (FEA) software for structural and thermal-structural response computations. The software package supports fully transient, nonlinear, coupled thermal-structural FEA, and can use nonlinear and temperature-dependent material properties. The package allows the application of a wide range of structural and thermal boundary conditions that include applied pressure, shear, displacement and rotation constraints, heat flux, convective heating, fixed temperature, and radiation. The boundary conditions can be simple constant values, or they can vary both spatially and temporally.
6. Utility programs [15]: These are numerous CFD-related programs developed in-house at NASA ARC for various projects (past and ongoing).

5. Results and Discussion

We next present a sampling of results from what we have accomplished thus far. The results are from exploratory studies and are best considered preliminary, especially since models for: (a) response of meteoritic material to imposed heating, and (b) structural and thermal-structural analysis are still under development while relevant properties (at higher temperatures) are being gathered.

5.1. Trajectory simulations

The mass loss equation used in meteor physics has been added into the trajectory simulation tool, *TRAJ* [7]. The code currently allows for the specification of a heat

transfer coefficient as a constant over the entire trajectory. Modeling of dependence of this coefficient on the velocity, altitude (density) and size of a spherical geometry is still under development. However, in the interim, the trajectory tool has been used to determine the shallowest possible entry flight path angle over ballistic coefficients ranging from 0 to about 500,000 kg/m² (Fig. 2).

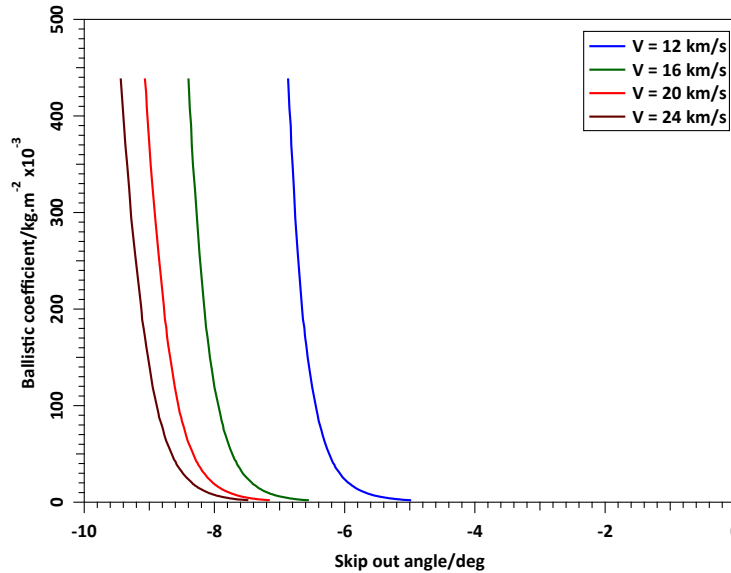


Figure 2. Skip out angle for ballistic coefficients ranging from 0 to 500,000 kg/m² and four entry velocities.

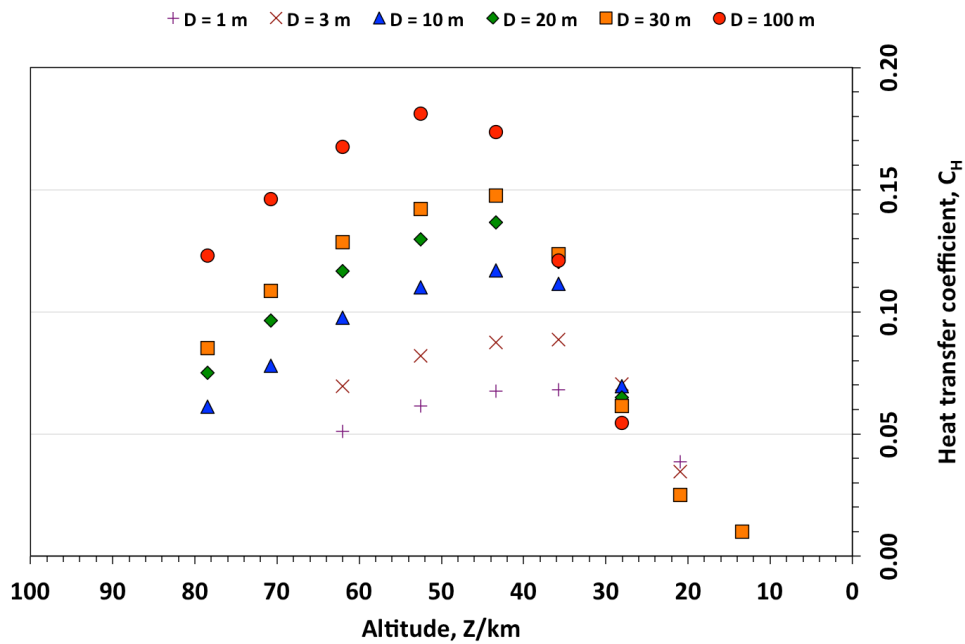
These results are useful for exploring the influence of entry flight path angle (defined as the angle reckoned from the local horizon with the negative sign indicating that the velocity is *below* the local horizon). A simple definition of the entry ballistic coefficient (for a spherical geometry) is $\beta = (4/3)\rho R/C_D$, where ρ is the bulk density of the meteoroid, R is the spherical radius, and C_D is the hypersonic drag coefficient of a sphere (≈ 0.9). Therefore, for a given material class (bulk density) and size, the limiting entry angle on the shallow end can be simply read off Fig. 2.

5.2. Aerothermal environments database for hemispheres

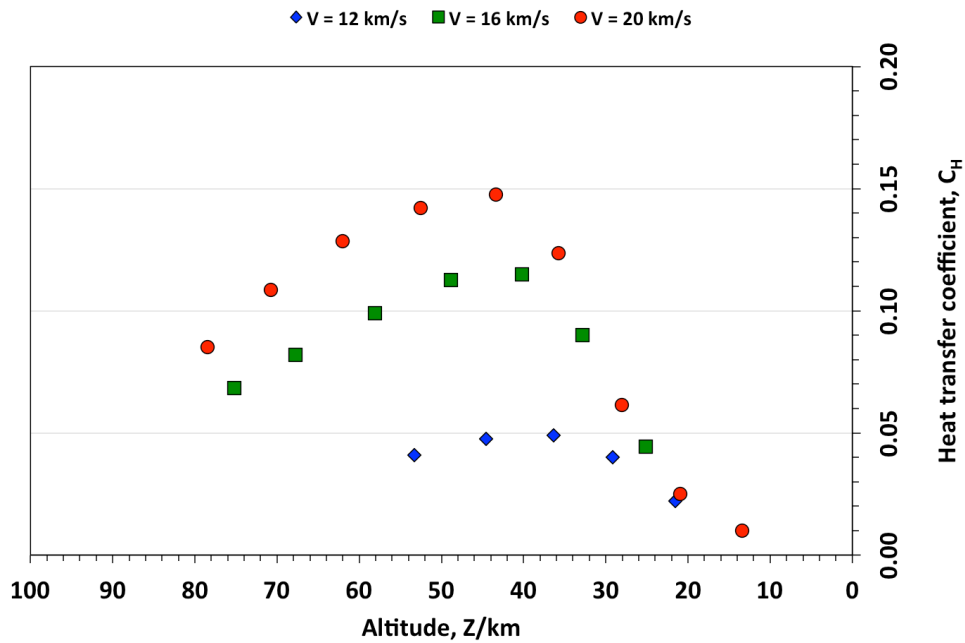
Axisymmetric flow computations were performed on *hemispherical* geometries (i.e., a wake is not included) for diameters ranging from 1 m to 100 m and for velocities ranging from 12 to 20 km/s. The objective was to determine the heating environments (convective and radiative) and visible light emission from the gas cap. In all cases the material is passive (no ablation) and the flow is assumed fully turbulent.

Variation with altitude of the computed heat transfer coefficient, C_H , for hemispheres of various sizes at a flight velocity of 20 km/s is shown in Fig. 3a, and the variation for a 30 m (diameter) hemisphere at three different flight velocities is shown in Fig. 3b. The maximum value of C_H occurs between 55 and 35 km altitude (decreasing altitude with decreasing size), and the values appear to collapse around 15 km altitude. It should be borne in mind that these results are from computations that assume *no ablation*, and magnitudes will change once material response is included. However, preliminary values of heat transfer coefficient are now available as a

function of velocity, altitude (proxy for density), and size, and the tables can be incorporated into the trajectory simulation tool; an appropriate interpolation scheme will be required for use in the mass loss equation.



(a) Variation with size for 20 km/s



(b) Variation with velocity for a 30 m (diameter) hemisphere

Figure 3. Computed heat transfer coefficient variation with altitude for: (a) hemispheres of various diameters for a velocity of 20 km/s, and (b) a 30 m diameter hemisphere at 3 velocities.

As a test of how far we could push our grid generation and simulation capability and get an idea of the level of effort necessary to execute the computations, we have also made an attempt at computing the flow around a real shape – asteroid Itokawa. We took the available CAD file and scaled the geometry from its original size of ≈ 500

m down to 20 m. This one-off computation was performed for a velocity of 20 km/s and a stagnation pressure of 30 bar. The choice of orientation was arbitrary, but additional computations can be performed for reasonably small variations in total angle of attack. Contours of surface pressure and convective heat flux are shown in [Fig. 4](#). Of note in the results is the increased pressure in the neck region of geometry – the pressure is roughly 1.5 times the stagnation pressure. We speculate that in the case of multi-lobed meteoroids, fragmentation is likely to start in this region.

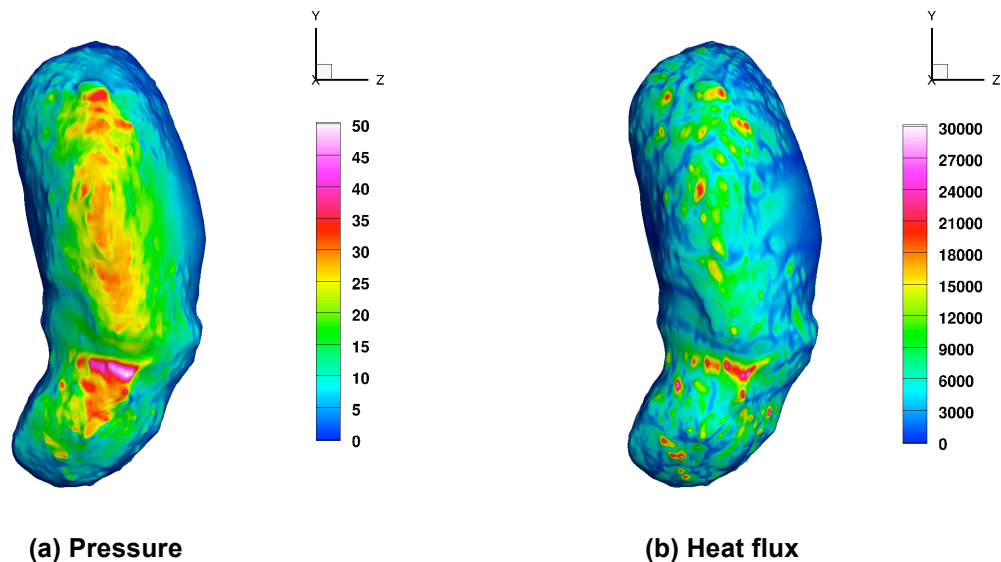


Figure 4. Surface pressure (in bar) and convective heat flux (in W/cm²) distributions for a 1/38-scale model of Asteroid Itokawa. Results are shown for a velocity of 20 km/s and a stagnation pressure of 30 bar. The flow is into the plane of the paper. Again, radiative heat flux is not included.

5.3. Additional computations

The influence of coupling of radiation to the flow was tested for a small number of cases (1 m diameter hemisphere at 12 and 16 km/s for a stagnation pressure of 10 bar). The change in the heat transfer coefficient with coupling was found to be between 10–20% lower than without coupling of flow and radiation. Clearly, the influence of radiation on the flow and vice versa is significant. Since our coupled computations are very slow and resource intensive, alternate methods [\[16–18\]](#) have to be explored.

A good portion of the current effort has been focused on flow computations because environments are needed for thermal and thermal-structural responses of materials, either as initial conditions, or as boundary conditions. Furthermore, these response models require more than just properties measured at room temperature; they require the temperature dependence as well. For meteoritic materials of interest to the PD effort at NASA ARC, not all properties are available, and these properties (and their measurement) are the purview of a PHA characterization team. In the interim, elemental composition of an ordinary chondrite was provided to the entry physics team [\[2\]](#). This composition was used within a suite of materials tools to construct what are known as B-prime tables [\[19\]](#). The B-prime parameter is a non-dimensional mass blowing rate typically tabulated over a range of temperatures and

pressures. B-prime tables are required for the analysis of ablative materials used in thermal protection systems of entry capsules. Tables of B-prime for an ordinary chondrite over a temperature range of 500–6000 K, and pressures ranging from 0.1 atm to 1000 atm, were constructed and a computation was performed with *FIAT* [12] at the stagnation point of a test article (made of ordinary chondrite material) at arc jet conditions. While these conditions do not correspond to flight, the computations do provide a good first test of the model implementation in *FIAT*.

Two- and three-dimensional discretizations of a 10 m diameter hemispherical asteroid were constructed for the first set of finite element thermal-structural analyses in *MARC* [14]. In these early computations, we have assumed the material to be uniformly dense fused silica quartz. For 2D/axisymmetric analysis, 4-noded quadratic elements were used, with mesh refinement at the wetted boundary to accommodate the expected steep temperature gradient due to high convective and radiative heating. The pressure, shear and heat flux from flow computations were imposed as boundary conditions on the wetted surface. The back surface was constrained to avoid any rigid body motion during the analyses. For 3D analysis, 8-noded hexahedral elements were used instead of tetrahedral elements; 8-noded elements provide better convergence in *MARC*. The coupled thermal-structural computations for the 2D/axisymmetric geometry showed that the contribution to stresses in the body due to thermal gradients and shear were insignificant compared with stresses due to pressure loads. Therefore, only structural analysis was performed for the 3D geometry subject to just pressure loads. Both the thermal-structural and structural computations helped establish grid and resource requirements for such analyses. In the longer term, we plan to perform thermal-structural and structural analyses using properties that are more appropriate for asteroid material, and include cracks and voids in the structure.

Assuming that a meteoroid is porous, we investigated a hypothesis that the penetration of hot plasma from the shocked gas into the porous medium of the meteor could cause it to fragment. Using the data available for meteor permeability [20], we found that the depth of plasma penetration compared to the size of objects we are interested in (10–30 m) is very small. Furthermore, including the effect of surface heating impedes the flow of gas into the medium – the gas is cooled as it penetrates deeper into the medium. It should be noted that these simulations did not account for ablation. For a recessing surface there would be further reduction in the depth of gas penetration. The problem needs to be investigated further, *i.e.*, with the inclusion of surface recession, to draw definite conclusions.

5.4. Multibody computations

Our early efforts have been largely focused on computations for a single body, *i.e.*, the entry object is a geometrically regular body of uniform mass distribution. In reality, the entry object could be a loosely bound (via some cohesive force) collection of smaller objects, or an irregular shaped object with two or more lobes. Consideration of multi-lobed shapes (regular or irregular) and collection of multiple objects is a necessary first step towards understanding not only fragmentation but also how multiple bodies interact with each other. For instance, multiple bodies in close proximity will experience increased aerodynamic loads and increased local heating (convective) due to shock-shock interactions, which in turn could affect the

light production from the gas cap and wake. For multiple bodies that are sufficiently separated in space one would have independent motion of several bodies, which could lead to a *reduction* in light production because of reduced radiating volumes of the gas cap and wake. Results from our first attempt at handling lobed shapes and multiple bodies are shown in Fig. 5. Since the geometries considered possess a rotational axis of symmetry, temperature contours are shown only in the pitch plane of symmetry with flow going from left to right. Clearly the shape, size, and number of bodies alter the flow structure in the wake. These very recent results have not yet been processed with the radiation computation tool *NEQAIR*. It should be noted here that our current methodology is only capable of handling “static” arrangements of multiple bodies, i.e., the flow computations do not include the dynamics of the bodies based on the aerodynamic forces (and moments). However, the relative arrangements of bodies might tell us something about the influence of shock-shock interaction on the light production.

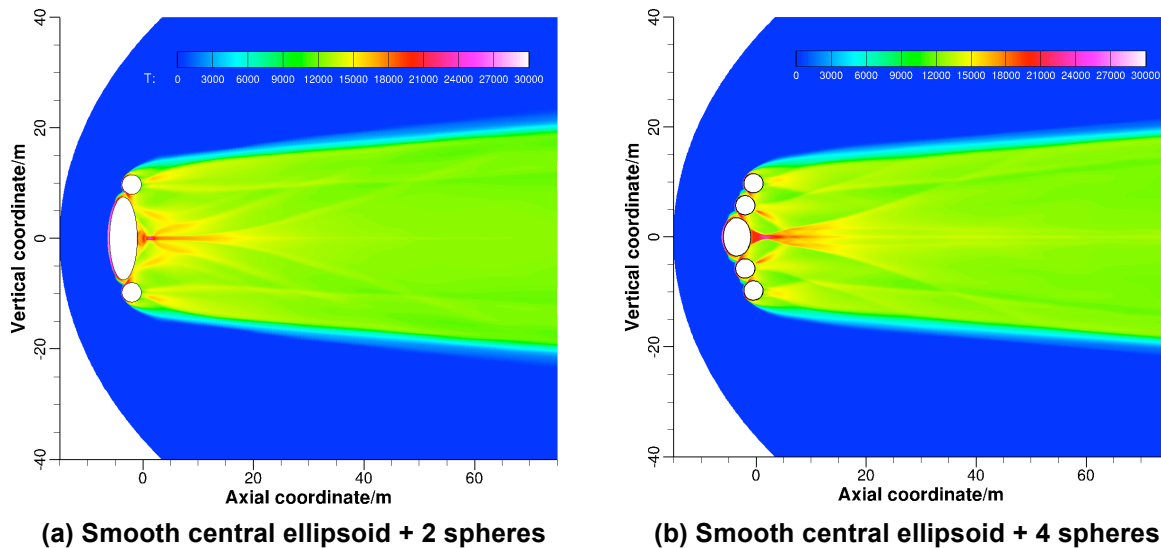


Figure 5. Pitch plane contours of temperature (in K) for a freestream condition of 20 km/s and stagnation pressure of 30 bar.

6. Concluding Remarks and Forward Work

Computations have been performed for hemispherical shape ranging from 1 m diameter to 100 m diameter and velocities ranging from 12 km/s to 20 km/s. For each combination of diameter and velocity, the altitude has been varied such that stagnation pressures between 0.1 bar and 300 bar would be achieved. From the computed solutions the heat transfer coefficients were determined for use in a trajectory code. Furthermore, we have made initial explorations in: (a) thermal response of meteoritic materials, (b) structural and thermal structural response of hemispheres subject to entry loads, (c) flow around collections of bodies, and (d) flow past a large size irregular object. More details of the present work can be found in NASA Technical Memorandum [21]. The present short effort has given the entry physics team a good idea of the scale and complexity of the problem of atmospheric entries of large size PHAs. However, there is a lot more to do to meet the overarching objectives: (i) modeling of energy deposition, and (ii) modeling of fragmentation.

Before taking on the long term objectives the team is currently focused on:

1. Enhancements of the thermodynamic and transport models to include multiply-ionized species – N^{2+} , N^{3+} , N^{4+} , O^{2+} , O^{3+} , and O^{4+} . Expanding the species set will open up the velocity space for analysis, so we can consider velocities greater than 20 km/s. Relevant thermodynamic properties are available in the work of Capitelli et al. [22]. Their data have a temperature limit of 50,000 K, and they have considered three levels – 250, 500, and 1000 cm^{-1} – of lowering of ionization potential..
2. Development of an efficient process to construct synthetic light curves from high-fidelity solutions for a single body at multiple points along its flight trajectory. An early version of such a process is already in place [23], and needs to be updated with the current versions of the simulation tools and utilities. The assumption here is that the trajectory simulation tool has been updated with time-varying heat transfer coefficients. Even if the high-fidelity solutions do not account for material thermal response, the synthetic light curves when compared against actual flight observations will provide a good idea of enhancement/reduction in light production. The main complication here is fragmentation, which will require a lot more work.

In the longer term, apart from flow simulations, the two main focus areas are:

1. Material thermal response and its coupling to flow computations. We recognize that the problem is complicated by the fact that the flow simulations have to be able to handle rapidly moving (recessing) surfaces, and intense radiative heating.
2. Structural response, primarily from a brittle fracture point of view. Initial simulations of thermal-structural response have shown that heat penetration into the interior is slow compared to the time of flight, and that only structural response needs to be studied. Although this reduces solution turnaround time, there is still the issue of voids and cracks in the structure. Furthermore, the influence of these on the aerothermal environment is not known.

Given our current understanding of the processes at work, and uncertainties about the material characteristics, including composition and state, our goal is to perform simulations starting with simplified models for well-known bolides, and to improve the fidelity of models in a systematic way, e.g., inclusion of physical features such as cracks, voids, etc. The light curves of observed bolides serve as useful benchmarks for comparing results from independent modeling and simulation. However, it is not yet clear if light curves tell us something about fragmentation processes at work. In some cases infrasonic signatures could provide a clue about major fragmentation events. Furthermore, the size distributions and impact footprints of meteorite falls could provide valuable guides to fragmentation altitudes.

Finally, we note that data from bolide observations alone may or may not be sufficient. As in the case of building spacecraft entry systems, well designed ground-based tests may help in verifying hypotheses we develop during the course of the present work, and perhaps help quantify the uncertainties in the predictions. We could use arc jets, ballistic range, shock tubes, and laser heating facilities. Even with such testing, the issue of traceability of ground-test data to flight will remain, since almost all of NASA's test facilities were intended to address atmospheric entries of capsules (or winged vehicles). Clearly, bringing higher fidelity modeling to bear on

the PHA problem is fraught with challenges, but it is an overdue endeavor that is as vital as any other in NASA's mission to benefit all humankind.

Acknowledgments

Authors DKP, PA, GAA, AMB, GEP, DAS, ECS, and MET were supported by NASA Contract NNA10DE12C to ERC, Inc. The authors are grateful to James Arnold, Craig Burkhard, Donovan Mathias, Derek Sears, Jessie Dotson, Anthony Dobrovolskis, Michael Aftosmis, Marian Nemec, and David Morrison for the frequent and helpful discussions we have had with them. The authors also thank Mark Boslough (SNL, Albuquerque, NM), and Profs. Peter Brown (U. Western Ontario, Canada) and Bruce Fegley (Washington U., St. Louis, MO) for illuminating discussions on meteor physics and chemistry.

References

1. Arnold, J. O., and Burkhard, C. D.: 2015, 'Overview of a New NASA Program Focused on Planetary Defense,' *Proceedings of 4th IAA Planetary Defense Conference*, Frascati, Rome, Italy (April 13-17, 2015).
2. Sears, D. W. G., *et al.*: 2015, 'Planetary Defense: A Meteorite Perspective,' *Proceedings of 4th IAA Planetary Defense Conference*, Frascati, Rome, Italy (April 13-17, 2015).
3. Mathias, D., : 2015, 'Meteor Breakup Modeling: Sensitivity of ground damage predictions to modeling assumptions,' *Proceedings of 4th IAA Planetary Defense Conference*, Frascati, Rome, Italy (April 13-17, 2015).
4. Prabhu, D. K., Loomis, M. P., Venkatapathy, E., Polsky, S., Papadopoulos, P., Davies, C. B., Henline, W. D.: 1998, 'X-33 Aerothermal Environment Simulations and Aerothermodynamic Design,' AIAA Paper No. 1998-0868.
5. Desai, N. P., and Qualls, G. D.: 2010, 'Stardust Entry Reconstruction,' *Journal of Spacecraft and Rockets*, **47**(5), pp. 736–740
6. Borovicka, J., Spurny, P., Brown, P., Wiegert, P., Kalenda, P., Clark, D., and Shrubeny, L.: 2013, 'The trajectory, structure, and origin of the Chelyabinsk asteroidal impactor,' *Nature*, **503**, pp. 235-237.
7. Allen, G. A., Jr., Wright, M. J., and Gage, P.: 2005, 'The Trajectory Program (Traj): Reference Manual and User's Guide,' NASA/TM-2004-212847.
8. Wright, M. W., White, T., and Mangini, N.: 2009, 'Data Parallel Line Relaxation (DPLR) Code User Manual Acadia – Version 4.01.1,' NASA/TM-2009-215388.
9. Cruden, B. A., and Brandis, A. M.: 2014, 'Updates to the NEQAIR Radiation Solver,' *Radiation in High Temperature Gases Workshop*, St. Andrews, UK, Nov. 24–28, 2014.
10. Palmer, G. E., White, T., and Pace, A.: 2011, 'Direct Coupling of the NEQAIR Radiation and DPLR Computational Fluid Dynamics Codes,' *Journal of Spacecraft and Rockets*, **48**(5), pp. 836–845.
11. Tauber, M. E., and Wakefield, R. M.: 1971, 'Heating Environment and Protection During Jupiter Entry,' *Journal of Spacecraft and Rockets*, **8**(6), pp. 630–636.
12. Chen, Y.-K., and Milos, F. S.: 1999, 'Ablation and Thermal Response Program for Spacecraft Heatshield Analysis,' *Journal of Spacecraft and Rockets*, **36**(3), pp. 475–483.

13. Chen, Y.-K., and Milos, F. S.: 2001, 'Two-Dimensional Implicit Thermal Response and Ablation Program for Charring Materials,' *Journal of Spacecraft and Rockets*, **38**(4), pp. 473–481.
14. MSC Software Corporation, 4675 MacArthur Court, Newport Beach, California 92660, USA.
15. <http://sourceforge.net/projects/cfdutilities/>.
16. Park, C.: 2014, 'Stagnation Region Radiative Ablation of Asteroidal Meteoroids in the Rosseland Approximation,' *Journal of Thermophysics and Heat Transfer*, **28**(4), pp. 598–607.
17. Golub, A. P., Kosarev, I. B., Nemchinov, I. V., and Shuvalov, V. V.: 1996, 'Emission and Ablation of Large Meteoroid in the Course of Its Motion Through the Earth's Atmosphere,' *Solar System Research*, **30**(3), pp. 183–197.
18. Kosarev, I. B., Loseva, T. V., and Nemchinov, I. V.: 1996, 'Vapor Optical Properties and Ablation of Large Chondrite and Ice Bodies in the Earth's Atmosphere,' *Solar System Research*, **30**(4), pp. 265–278.
19. Anon.: 1987, 'User's Manual: Aerotherm Charring Material Thermal Response and Ablation Program,' Acurex UM-87-13/ATD, Acurex Corporation, Aerotherm Division, Mountain View, CA.
20. Corrigan, C. M., Zolensky, M. E., Dahl, J., Long, M., Weir, J., Sapp, C., and Burkett, P. J.: 1997, 'The porosity and permeability of chondritic meteorites and interplanetary dust particles,' *Meteoritics and Planetary Science*, **32**(4), pp. 509–515.
21. Prabhu, D. K., et al.: 2015, 'Physics-Based Modeling of Meteor Entry and Breakup,' NASA TM (in preparation).
22. Capitelli, M., Colonna, G., Giordano, D., Marraffa, L., Casavola, A., Minelli, P., Pagano, D., Pietanza, L. D., and Taccogna, F.: 2005, 'Tables of Internal Partition Functions and Thermodynamic Properties of High-Temperature Mars-Atmosphere Species from 50K to 50000K,' ESA STR-246.
23. Liu, Y., Prabhu, D., Trumble, K. A., Saunders, D., and Jenniskens, P.: 2008, 'Radiation Modeling for the Reentry of Stardust Sample Return Capsule,' *Journal of Spacecraft and Rockets*, **47**(5), pp. 741–752.